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OPTIMIZATION OF MACHINING PARAMETERS USING DESIRABILITY FUNCTION ANALYSIS AND ANOVA FOR THERMO-MECHANICAL FORM DRILLING

S. INDUMATHI[1] V. DIWAKAR REDDY[2] & G. KRISHNAIAH[3]

[1]Department of Mechanical Engineering, NBKR Institute of Science & Technology,
Vidyanagar, Tirupathi, Andhra Pradesh, India

[2,3]Department of Mechanical Engineering, S.V. University College of Engineering,
Tirupathi, Andhra Pradesh, India

ABSTRACT

This paper presents optimization of machining parameters for thermo – mechanical form drilling of Aluminum sheet (AA1100) using desirability function analysis (DFA). The experiments were conducted using Taguchi's L_9 orthogonal array on conventional drilling machine with tungsten carbide tool. The machining parameters such cone radius ratio , spindle speed and feed rate are optimized by multi-response considerations namely temperature ,bush length and surface roughness .The optimal machining parameters have been determined by the composite desirability value obtained from desirability function analysis, and significant contribution of parameters can be determined by analysis of variance (ANOVA). The analysis results shows that optimal combination for high temperature, good bush length and surface roughness are high spindle speed, high feed rate and high cone radius ratio. Confirmation test is also conducted to validate the test results. Experimental results have shown that machining performance can be improved effectively through this approach.

KEYWORDS: Form Drilling, ANOVA, Bush Length, Desirability Analysis (DFA), Form Drilling

INTRODUCTION

Form drilling is a bush making process applied to sheet metals, thin walled tubes or profiles for joint engagement. In manufacturing engineering, the assembly of sheet metals, thin walled tubes or profiles is one of the major problems. These jobs could be performed using form drilling process, which enable to simplify assembly process and to improve reliability of the joint. This method avoids additional manufacturing like weld nuts or assembly of J-nuts.

Contrary to traditional drilling, in form drilling there is no material removal but displacement of material. The bush is formed from the parent material which is subjected to frictional heating, but the end of the bush material has a finer structure because of dynamic recrystallization. This special feature cannot be achieved by normal drilling process. Form drilling is an operation controlled by friction heating starting from initial indentation, under constant axial pressure, the heated metal work piece is extruded both upwards and downwards in the ratio of 40% to 60% respectively. The height so formed bush measures 2.5 to 3 times the original thickness of the material [1]. Due to local friction heating of work piece, the operation can be performed with a relatively small axial pressure, so that no special measures to support blind Sections. The additional feature of form drilling is it does not require any lubricant during the process. The fumes of lubricant impacts human health and work place environment.

Miller et al. [2] developed two models for friction drilling. One is the thermal finite element model to predict the distance of tool travel before the work piece reaches the 250°C threshold temperature that is detectable by an infrared camera. Another is a force model to predict the thrust force and torque in friction drilling based on the measured

temperature, material properties, and estimated area of contact. Miller et al. [3] conducted experiments and indicated that materials with different compositions and thermal properties affect the selection of friction drilling process parameters, the surface morphology of the bore, and the development of a highly deformed layer adjacent to the bore surface. Miller et al. [4] suggested that pre-heating the brittle material (cast metals) work piece and high speed friction drilling process could generate a cylindrical-shaped bushing without significant radial fracture. Wei-Liang Ku [5] developed new thermal friction drill with sintered carbide, and optimized machining process by Taguchi method. Significance of process parameters on machining characteristics was examined by ANOVA.

The above related papers not described optimization of multiple performance characterization. Desirability function analysis (DFA) can provide efficient solution to the uncertainty in multi-input and discrete data problems. It had been most widely used in industry to optimize the multi-response process the multi response characteristics into single response characteristics. It is an effective method to analyze the relational degree between discrete sequences. The advantage of the above method is that many factors can be analyzed using less data. It does not involve complicated mathematical theory or computation like traditional approaches and thus can be employed by engineers without strong statistical background. The approach about desirability function analysis and its applications are illustrated in [6-9]. From the literature , it has been observed that Taguchi methodology can be applied to for analyzing the best process parameters for single performance characteristics only , where as desirability function analysis can be effectively used for analyzing the multi performance characteristics incorporating the above all parameters at a time.

The main objective of this paper is to present the optimize the machining parameters of the form drilling process on aluminum alloy (AA1100) with tungsten carbide tool. Moreover, the desirability function analysis was adopted to convert the multiple performance characteristic in one numerical score called composite desirability value. Based on composite desirability value, the optimal level of parameters can be obtained. The Taguchi's L_8 orthogonal array is utilized for experimental investigation. The experimental data were statistically surveyed by analysis of variance (ANOVA) to investigate the most influencing parameters on temperature, bush length and surface roughness.

Experimental Details

The form drill was made by tungsten carbide of cylindrical bar with super fine grain size. The form drill was ground into conical shape using diamond grinder shown. In this study, the work piece material was AA1100 aluminum alloy plate with dimensions of 50 X 50 X 3 mm, and the drilled holes on the plate had a diameter of 6 mm made using Radial pillar drilling machine. This study utilized the form drilling conditions as 700~800 rpm drilling speed and 0.15 0.2 mm/rev. feed rate to conduct the experiments.

Figure 1 showed a schematic diagram of the experimental setup for form drilling. The responses consider in this study were temperature, bush length and surface roughness. The temperature was measured with non contact infrared temperature gun, the bush length was measured by a tool – maker microscope, and the surface topographies of the drilled holes were observed by scanning electron microscope (SEM) to inspect their surface integrity. The form drilled holes are shown in Figure 2.

Figure 1: Form Drilling Operation

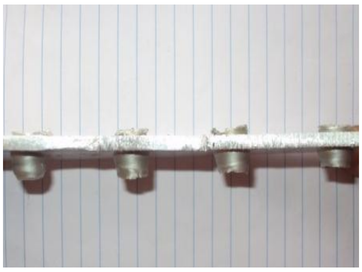

Figure 2: Form Drilled Holes on Al1100 Plate

To perform the experimental design, a total of three parameters namely cone radius ratio (A), spindle speed (B) and feed rate (C) were chosen for the controlling factors, and each parameter is designed to have two levels, namely low and high as shown in the table 1.It was also decided to study the two factor interaction effects on multiple performance characteristics. The selected interactions were between cone radius ratio and speed ($A\times B$), between cone radius ratio and feed rate ($A\times C$), and spindle speed and feed rate ($B\times C$). In this study, an orthogonal array L_8 based on Taguchi method was applied to design of experiments. The experimental results are summarized in table 2.

Table 1: Process Parameters and Their Levels

Factors	Process Parameters	Units	Levels	
			1	1
A	Cone radii ratio	----	2.0	3.0
B	Spindle speed	Rpm	700	800
C	Feed rate	mm/rev	0.15	0.2

Table 2: Experimental Plan with Responses

Exp. No.	Process Parameters			Responses		
	A	B	C	Temp. T^oc	Bush Length, BL(mm)	Surface Roughness. Ra(μm)
1	1	1	1	123	6.3	4.46
2	1	1	2	122	6.7	4.72
3	1	2	1	147	7.2	3.72
4	1	2	2	143	7.6	3.92
5	2	1	1	136	6.7	4.76
6	2	1	2	138	6.9	4.89
7	2	2	1	152	7.7	3.38
8	2	2	2	157	7.9	3.41

Desirability Function Analysis

Desirability function analysis (DFA) is one of the most widely used methods in industry for the optimization of multi – response characteristics. Desirability function analysis is used to convert the multi response characteristics into single – response se characteristics. As a result, optimization of complicated multi – response characteristics can be converted into optimization of a single response characteristic termed composite desirability. The multi responses such as temperature, bush length and surface roughness are combined as composite desirability using desirability function analysis.

Optimization Steps Using Desirability Function Analysis

Step 1: calculate the individual desirability index (D_i) for the corresponding responses using formula proposed by the Derringer et al.[10].there are three types of the desirability functions according to the response characteristics.

- **The-Nominal-the Best:** value of $\hat{y}$ is required to achieve a particular target T. When the $\hat{y}$ equals to T, the desirability value equals to 1; if the departure of $\hat{y}$ exceeds a particular range from the target, the desirability value equals to 0, and such situation represents the worst case. The desirability function of the nominal-the-best can be written as given in (1).

$$D_i = \begin{cases} \left(\frac{\hat{y}-y_{min}}{T-y_{min}}\right)^s, & y_{min} \le \hat{y} \le T,\ s \ge \\ \left(\frac{\hat{y}-y_{max}}{T-y_{max}}\right)^t, & T \le \hat{y} \le y_{max},\ t \ge \\ 0, & \end{cases} \tag{1}$$

Where, y_{max} and y_{min} represent the upper and lower tolerance limits of, and s and t represent the weights.

- **The-Larger-the Better:** The value of $\hat{y}$ is expected to be the larger the better. When the $\hat{y}$ exceeds a particular criteria value, which can be viewed as the requirement, the desirability value equals to 1; if the $\hat{y}$ is less than a particular criteria value, which is unacceptable, the desirability value equals to 0. The desirability function of the larger- the better can be written as given in (2).

$$D_i = \begin{cases} 0, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y}-y_{min}}{y_{max}-y_{min}}\right)^r, & y_{min} \le \hat{y} \le y_{max},\ r \ge \\ 1, & \hat{y} \ge y_{min} \end{cases} \tag{2}$$

Where, y_{min} represents the lower tolerance limit of y_{max} represents the upper tolerance limit of and r represents the weight.

(c) **The-Smaller-the Better**: The value of $\hat{y}$ is expected to be the smaller the better. When the $\hat{y}$ is less than a particular criteria value, the desirability value equals to 1; if the $\hat{y}$ exceeds a particular criteria value, the desirability value equals to 0. The desirability function of the-smaller-the-better can be written as given in (3)

$$D_i = \begin{cases} 1, & \hat{y} \le y_{min} \\ \left(\frac{\hat{y}-y_{max}}{y_{min}-y_{max}}\right)^r, & y_{min} \le \hat{y} \le y_{max},\ r \ge \\ 0, & \hat{y} \ge y_{max} \end{cases} \tag{3}$$

where, y_{min} represents the lower tolerance limit of, y_{max} represents the upper tolerance limit of and r represents the weight. The s,t and r in Esq. 1, 2 and 3 indicate the weights and are defined according to the requirement of the user. If the corresponding response is expected to be closer to the target, the weight can be set to the larger value; otherwise, the weight can be set to the smaller value.

In this study, "the smaller the better" characteristic is applied to determine the individual desirability values for surface roughness, and "the larger the better" characteristic is applied to determine the individual desirability values for material removal rate.

Step 2: Compute the composite desirability (D_G). The individual desirability index of all the responses can be combined to form a single value called composite desirability (D_G) by the following (4).

$$D_G = \sqrt[w]{(D_1^{w_1} * D_2^{w_2} \ldots\ldots\ldots\ldots..* D_i} \tag{4}$$

where, D_i is the individual desirability of the property Y_i, w_i is the weight of the property "Y_i" in the composite desirability and w is the sum of the individual weights.

Step 3: Determine the optimal parameter and its level combination. The higher composite desirability value implies better product quality. Therefore, on the basis of the composite desirability (D_G), the parameter effect and the optimum level for each controllable parameter are estimated.

Step 4: Perform ANOVA for identifying the significant parameters. ANOVA establishes the relative significance of parameters. The calculated total sum of square values is used to measure the relative influence of the parameters.

Step 5: Calculate the predicted optimum condition. Once the optimal level of the design parameters has been selected, the final step is to predict and verify the quality characteristics using the optimal level of the design parameters.

Table 3: Evaluated Individual Desirability and Composite Desirability

Exp No.	Cone Radius Ratio, A	Spindle Speed, B (rpm)	Feed Rate, C (mm/rev)	Individual Desirability (D_i)			Composite Desirability (D_G)
				T, ^{0}c	R_a(μm)	BL(mm)	
1	2	700	0.15	0.02857	0.2847	0.0000	0.0000
2	2	700	0.2	0.0000	0.1125	0.7500	0.0000
3	2	760	0.15	0.7142	0.7748	0.4375	0.4920
4	2	760	0.2	0.5714	0.6423	0.1875	0.06881
5	3	700	0.15	0.4000	0.9139	0.7500	0.27417
6	3	700	0.2	0.45714	0.0000	0.6250	0.0000
7	3	760	0.15	0.8571	1.0000	0.1250	0.1071
8	3	760	0.2	1.0000	0.9801	1.0000	0.9801

RESULTS AND DISCUSSIONS

In the form drilling process, higher temperature, higher bush length and lower surface roughness are indications of better performance. Taguchi's L_8 orthogonal array was used for experimental investigation. The experimentally collected data were subjected to desirability function analysis and ANOVA for optimization of machining parameters. For data pre-processing in the desirability function analysis process, temperature is taken as "larger is better" surface roughness is taken as the "smaller is better" and bush length is taken as the "larger is better".

Results of Individual and Composite Desirability

Optimal combinations of parameters are determined based on assumed weightage. The weight age of parameters was assumed on the basis of physical significance of each parameter during machining. Temperature, bush length and surface roughness plays an important role in many areas for evaluation of machining accuracy. In this work equal weightage is considered for all the responses to predict the optimum machining parameters.

The individual desirability values are calculated using Eq. 3 for surface roughness and using Eq. 2 for temperature and bush length are presented in Table 3. Based on assumed weightage, the composite desirability values are also calculated using Eq. 4 and tabulated in Table 3. The higher composite desirability value represents that the corresponding experimental result is closer to the ideally normalized value. In other words, optimization of the complicated multiple performance characteristics can be converted into optimization of a single composite desirability value.

Effect of Process Parameters on Composite Desirability

The effect of different machining parameters on AA1100 can be studied by using response graph and response table. The mean response values for each level of parameter on composite desirability is calculated and presented in Table 4 and graphically shown in Figure 3. Basically, the larger the composite desirability, the better is the multiple performance characteristics. From the response graph and response table the best values of various parameters for the combined

objective of minimum surface roughness and maximum bush length and temperature are identified as high cutting speed, high feed rate and high cone radius ratio (A_2 B_2 C_2). The interaction plots for composite desirability values shown in Figure. 4 are between cone radius ratio and spindle speed ($A \times B$), between cone radius ratio and feed rate ($A \times C$), and between spindle speed and feed rate ($B \times C$). It is observed from the interaction plots for composite desirability that there is an interaction between cone radius ratio and feed rate and spindle speed and feed rate there is very weak interaction between all the other process parameter in affecting composite desirability.

ANOVA for Composite Desirability

Analysis of variance (ANOVA) is a method of apportioning variability of an output to various inputs. The purpose of the statistical ANOVA is to investigate which design parameter significantly affects the performance characteristic. This is accomplished by separating the total variability of the composite desirability value, which is measured by the sum of the squared deviations from the total mean of the composite desirability value, into contributions by each machining parameter and the error. First, the total sum of the squared deviations SS_T from the total mean of the composite desirability value γ can be calculated as:

Table 4: Response Table for the Composite Desirability

Machining Parameter	Average Composite Desirability		Max-Min
	Level 1	Level 2	
Cone radius , A	0.1402	0.3403	0.2001
Spindle speed, B (rpm)	0.0685	0.4120	0.3435
Feed rate, C (mm/rev.)	0.2183	0.2622	0.0439
Total Mean of the Composite Desirability = 0.2402			

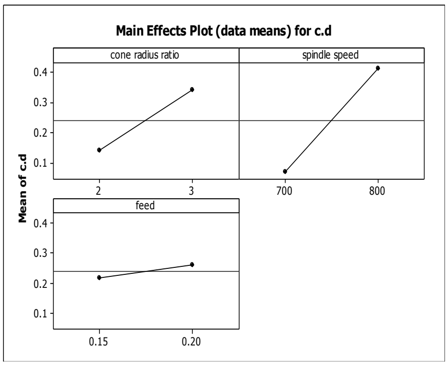

Figure 4: Response Graph for Composite Desirability

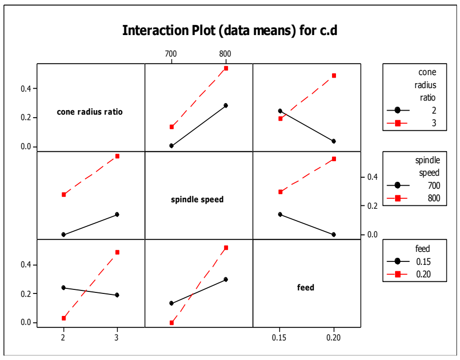

Figure 5: Interaction Plots for Composite Desirability

Table 5: ANOVA for Composite Desirability (D_g)

Factor	Sum of Square (SS)	DOF	Mean Square (MS)	F-Test	P (%)
A	0.1954	1	0.1187	0.16	8.55
B	0.6305	1	0.2050	0.28	27.59
C	0.0450	1	0.5120	0.69	1.9
A*B	0.214	1	0.02140	0.03	9.36
A*C	0.3201	1	0.3201	0.43	14.01
B*C	0.3300	1	0.3300	0.44	14.44
Error	0.7423	1	0.7423		0.3249
Total	2.2847	7			100

Confirmation Test

Once the optimal level of machining parameters is selected, the final step is to predict and verify the improvement of the performance characteristics using the optimal level of the machining parameters. The estimated composite desirability value $\hat{\gamma}$ using the optimum level of the machining parameters can be calculated as:

$$\hat{\gamma} = \gamma_m + \sum_{i=1}^{n} (\overline{\gamma_j} - \gamma_m) \tag{5}$$

where, γ_m is the total mean of the composite desirability value $\overline{\gamma}_j$, is the mean of the composite desirability value at the optimum level and n is the number of machining parameters that significantly affects the multiple performance characteristics. Based on (5) the estimated composite desirability value using the optimal machining parameters can then be obtained. Table 5 shows the results of the confirmation experiment using the optimal machining parameters. Temperature is improved from 136 ^oc to 152 ^oc Surface roughness R_a is reduced from 4.76 to 3.38 μm and the bush length is greatly improved from 6.7 to 7.7. It is clearly shown that multiple performance characteristics in the form drilling process are greatly improved through this study. Desirability function analysis and ANOVA for optimization of machining parameters. From this analysis, the following conclusions were drawn.

- The spindle speed (Percentage contribution, P = 27.59%) is the more significant machining parameter for affecting the multiple performance characteristics form drilling process.
- High spindle speed, high feed rate and high cone ratio (A_2 B_2 C_2) are the optimum machining conditions.
- The performance characteristics such as temperature, surface roughness and bush length are improved together by using the above proposed method.

Table 6: Results of Confirmation Test

Initial Machining Parameters	Optimal Machining Parameter		
		Prediction	Experiment
Levels	$A_1B_1C_1$	$A_2B_2C_3$	$A_2B_2C_2$
Temperature,^{o}c	136		152
Bush length,mm	6.7		7.7
Surface roughness,μm	4.76		3.38
Composite desirability	0.27417	0.5341	0.9801
Improvement in composite desirability =0.4071			

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